FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Estimating the Remaining Lifetime of Power Transformers Using Paper Insulation Degradation

Nuno Morais

Mestrado Integrado em Engenharia Eletrotécnica e de Computadores

Supervisor: Professor Luís Guimarães

July 24, 2018

Resumo

Transformadores de potência são equipamentos essenciais para o bom funcionamento de uma rede eléctrica. Devido ao seu elevado custo e a todos os inconvenientes que a paragem de funcionamento de um transformador pode causar, é importante que as empresas que possuem este tipo de equipamentos possam prever qual o tempo útil de vida restante dos mesmos. Esta necessidade torna-se ainda mais acentuada, quando a esperança média de vida, que na maioria dos transformadores corresponde a aproximadamente 40 anos, já foi ultrapassada. Esta situação verifica-se com frequência nos equipamentos instalados onde, em alguns casos, já foram atingidos os 60 anos de idade.

Desta forma, o presente trabalho incide na conceção e implementação de uma metodologia que permita estimar o tempo restante de vida dos transformadores de potência, permitindo assim aos seus proprietários realizar um planeamento adequado e atempado de manutenção e possível substituição.

Esta estimação é feita através da análise do estado de degradação do papel isolante, sendo para isso analisada a concentração de 2-furfuraldeído e o valor de *Degree of Polymerization*.

A viabilidade do método desenvolvido é avaliada através de testes realizados com medições reais em Transformadores de Potência e da comparação entre testes onde as trocas de óleo não foram consideradas e testes onde estas foram contempladas.

Abstract

Power transformers play a major role in electrical networks. Due to their high price and the inconveniences that may derive from them reaching the end of their life cycle, it is crucial that companies who depend on this type of equipment may predict what is its remaining lifetime. This prediction becomes even more important when the expected useful life, which in most power transformers is approximately 40 years, has been overcome. This specific situation is very common and, in some cases, there are 60 years old devices.

Therefore, the present work conceives and implements a methodology that allows estimating the remaining lifetime of power transformers, making it possible for owners to make an adequate and early plan for maintenance and replacement when it is needed.

This estimation is made using the paper insulation degradation, with the analysis of 2-furaldehyde content and *Degree of Polymerization* measures.

This method's viability is evaluated by performing tests with real Power Transformers' data and comparing tests with no oil changes considered and tests where this changes were taken into account.

Agradecimentos

Embora a escrita deste documento tenha sido realizada em inglês, decidi escrever os meus agradecimentos em Português.

Assim, gostaria de começar por agradecer ao meu orientador, Professor Luís Guimarães e ao Engenheiro Luís Dias, do Centro de Engenharia e Gestão Industrial do INESC TEC, por toda a disponibilidade e paciência demonstradas desde o início desta tese bem como por toda a ajuda.

Aos meus pais, por todo o apoio que sempre me deram em todas as minhas decisões e por tudo o que me ensinaram e transmitiram ao longo da minha vida.

Ao meu irmão, Gonçalo Morais, por todas as dores de cabeça, palhaçadas e desabafos. Por estares sempre lá para mim, mesmo nem sempre o demonstrando.

Ao meu avô, Lindolfo Osório, por todos os valores transmitidos e por sempre teres acreditado em mim, fazendo de mim aquilo que sou hoje.

À Antónia, pela amizade e carinho e por estares sempre presente, independentemente das circunstâncias.

Aos amigos que a FEUP me deu, Catarina Soares, Daniela Oliveira, Diogo Azevedo, Rafael dos Santos, Nuno Reininho e Henrique Mendes por todos os bons momentos passados ao longo destes últimos anos. Por todas as pausas e noitadas juntos, todas as alegrias e tristezas partilhadas, por todas as gargalhadas proporcionadas. Espero que possamos continuar a repeti-lo daqui para a frente.

Ao Tiago Santos, um especial obrigado pela inscansável ajuda e disponibilidade, por todas as noitadas e momentos de risota que tivemos, mas acima de tudo obrigado pela amizade e pelas palavras de motivação quando mais precisei.

Aos meus amigos Catarina Mavilde, Gonçalo Tomé, Rita Pinho, e Bruno Almeida por terem estado sempre presentes ao longo destes últimos anos e por todos os momentos que passámos juntos.

À "tia" Helena Pinho, pelas palavras certas nas horas certas, e por me ter levado sempre para o melhor caminho, o meu muito obrigado.

Aos amigos de sempre, Andreia Silva, André Rodrigues, António Barbosa, João Pombo, Luís Sousa, Paula Duarte, por todos os momentos partilhados, por crescermos juntos e pela indiscritível amizade que está sempre presente.

Por fim agradecer ao meu principal pilar, à minha namorada Rute Medeiros, por toda a paciência, toda a ajuda e, acima de tudo, por estar sempre do meu lado! Sem ti tudo isto teria sido muito mais difícil.

A todos estes, e tantas outras pessoas que de alguma forma marcaram o meu percurso,

Muito Obrigado

Nuno Morais

"The important thing is to not stop questioning.
Curiosity has its own reason for existing"

Albert Einstein

Contents

List of Figures

List of Tables

Abbreviations and Symbols

2FAL	2-furaldehyde
AD	Absolute Deviation
CBM	Condition Based Maintenance
CM	Corrective Maintenance
D	Deviation
DETC	DE-energized Tap Changer
DGA	Dissolved Gas Analysis
DP	Degree of Polymerization
DPM	Duval Penthagon Method
DTM	Duval Triangle Method
EOL	End Of Life
KGA	Key Gas Analysis
OLTC	On Load Tap Changer
PG	Power Grid
PM	Preventive Maintenance
PT	Power Transformer
RBM	Risk Based Maintenance
RRM	Roger’s Ratio Method
TBM	Time Based Maintenance

Chapter 1

Introduction

The present document is a dissertation for the Master Course in Electrical and Computer Engineering at the Faculty of Engineering of the University of Porto and its main purpose is to develop a method that will estimate a Power Transformer's (PT) end of life (EOL), and consequently, its remaining lifetime, considering 2-furaldehyde (2FAL) variations.

This chapter aims to introduce this thesis, specifying its objectives, as well as this document's structure.

1.1 Context and Motivation

Asset management has become a core activity in companies due to the impact it can have on their finances. Thanks to an integrated and planned approach, companies are able to prevent potential expenses, by taking the adequate measures so that maintenance costs are as minimum as possible without compromising the asset performance and availability. Furthermore, it facilitates an early planning for maintenance, allowing for the extension of the assets' lifetime.

When working with oil immersed PTs, asset management is essential due to numerous reasons such as their replacement and repairing costs, the impact of a failure or breakdown in the power grid (PG) and accidents that may occur due to malfunctioning in PTs.

A correct definition of a maintenance policy of a PT is a crucial procedure (e.g. time-based maintenance, condition-based maintenance [3]) to extend their lifetime as much as possible, thus companies that own these equipments are continuously looking for new solutions that will allow them to decide what is the best procedure to follow given an estimation of the current remaining lifetime. These solutions are becoming of increasingly importance due to the advanced age of current PTs.

The insulation of an oil immersed PTs is guaranteed by oil and insulation paper. Throughout time, these two components will degrade, losing their dielectric and mechanical strength which affects their performance and so, the PT's insulation will be less effective. In order to fix this, as well as to prevent faults and extend a PTs lifetime it is necessary to perform maintenance procedures to these components. However, it should be considered that these can only be applied to oil since insulation paper is very difficult to replace and so, when it reaches the end of its useful life, the PT reaches the end of its lifetime too. Oil, however, can be filtered or even replaced, improving this way the insulation effectiveness. [6]

Bearing in mind that paper can not be replaced it is crucial to understand its condition by study the *Degree of Polymerisation (DP)*. DP is the value that represents paper insulation's condition. When the paper is new, its DP should be about 1200 and it is considered to have reached the end of its lifetime when its DP is around 200 [4]. By knowing this value, it is easier to estimate a PT's EOL, and therefore, its remaining lifetime (Figure 1.1). This could be done by getting a paper sample and analysing it, but since it is something very difficult to do, this is done by studying 2FAL concentration in oil. 2FAL concentration increases as paper degrades since paper degradation produces this furan, which gets dissolved in oil.

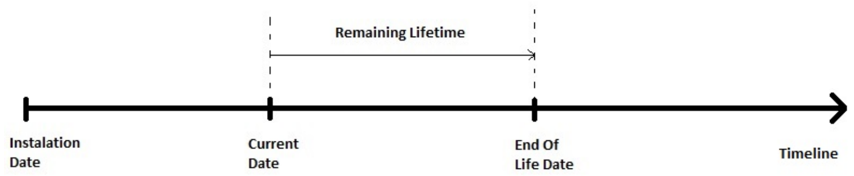

Figure 1.1: Distinction between Remaining Lifetime and End of Life

Although 2FAL concentration can be measured by performing an oil analysis it is difficult to estimate the real DP value based on this measure because 2FAL only provides an approximate value of the DP. Moreover, 2FAL concentration drops at every oil change affecting DP results and in most of the literature approaches, oil changes are not considered when performing this estimation.

Nowadays, several methods are available to estimate the PT's remaining lifetime (i.e. fuzzy logic systems and artificial neural networks). However, due to the conditions PTs face while they are operating, and even due to some maintenance measures, predictions are not always accurate.

In this thesis, a solution that estimates DP at every moment is developed, taking into account oil changes which can make EOL estimation more accurate. This method was developed based on real data which is essential to understand and predict every phenomenon related to PT's activity.

1.2 Objectives

This work aims to find an accurate way of predicting the remaining lifetime of a PT by studying its paper insulation degradation. Although it is not currently possible to develop an infallible method, due to all the existing restrains, it is hoped that the one developed will have a better performance than the current methods.

Therefore, this thesis outlines the following objectives:

- To study and present different methods for estimating a PT's remaining lifetime and of its maintenance.

- To develop an algorithm, that will take in consideration real data measured from PTs, and with that, might be able to estimate the PT's remaining lifetime.
- To implement and test such algorithm with real data, presenting the obtained results.

1.3 Thesis Methodology

During the development of this thesis, literature review regarding PTs, its types of maintenance and methods available for condition evaluation and remaining lifetime estimation was performed.

After this literature review, the provided dataset were analysed and processed in order to filter the most important data for this thesis development. Having processed all the data, a method that would estimate a PTs end of life was planned, being considered different approaches that would seem reliable. Once the approach to use was decided, the planned algorithm was implemented using Matlab.

Once the algorithm was functional and providing results, tests were performed taking into account different types of situations that could happen when estimating a PT's EOL.

These results were later compared with each other.

1.4 Document Structure

This document contains 6 chapters and is outlined as follows. In Chapter 2 a literature review of the concepts related to this thesis and the most used methods for PT's maintenance and remaining lifetime prediction are presented. Chapter 3 presents the chosen method to perform and the mathematical formulation is introduced. In Chapter 4 the developed algorithm is presented and explained in detail. Chapter 5 presents the performed tests, as well as its results and respective discussion. Chapter 6 concludes this document discussing the main conclusions and referring possible future work.

Chapter 2

State of the Art

One of the main components of a PG is a PT. Their maintenance is crucial to guarantee the PG's well functioning as well as to prevent significant damages and inconveniences that their failure might cause. Apart from that, a correct maintenance might extend a PT lifetime, creating the possibility to its owner to manage the best time to replace it, according to the company's most suitable work plan and financial status [6].

A PT lifetime may be affected by the degradation of some subsystems such as the dielectric (affected by PTs insulation and windings condition), magnetic circuit (depends on core condition), tap changers (subsystem that controls the PT's voltage levels) and mechanical parts (bushings, tank, cooling tubes,etc.) [7, 8].

In this chapter, an introduction to PTs is presented, including what their main components are, followed by a review of the types of maintenance and current methods used to monitor PT's condition as well as to estimate its remaining lifetime.

2.1 Power Transformers Structure

PTs play a major role in PGs being responsible for adapting voltage levels according to the grid's needs [9]. Being such an important and complex device, a PT consists of multiple subsystems (Figure 2.1) such as windings, core, tap changer, bushings and insulating materials. Some of this components are replaceable (e.g. bushings) where others are not (e.g. tap changer, windings, insulating materials) [9, 10].

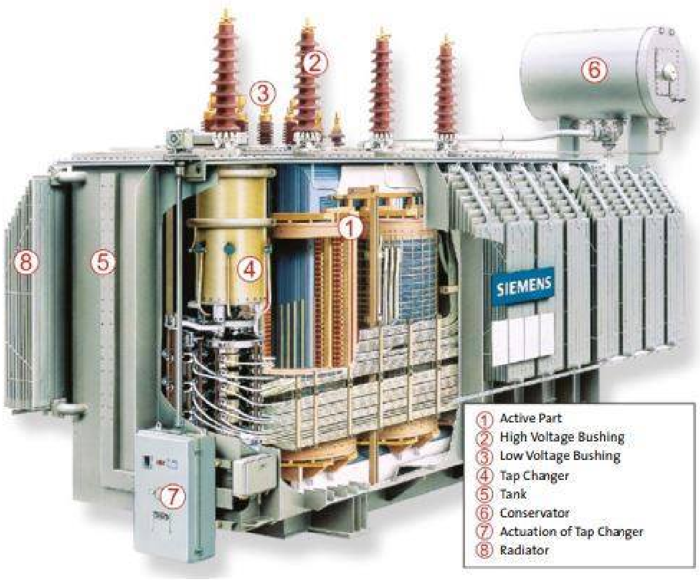

Figure 2.1: Structure of a Power Transformer [1]

Windings and Core are the main elements of a PT. The windings are handmade out of copper and can be of core type or shell type accordingly to the position of the core. They are covered with an insulation paper that provides greater dielectric and mechanical strength. The core is made out of steel and has great magnetic permeability providing low resistance to the magnetic flux. They must enable a path for the magnetic flux to flow between windings reducing losses to the lowest possible value [9].

The tap changer is a device that allows the PT to adjust itself to the grid's needs. For example, if there is a higher energy demand, voltage levels will drop so the tap changer will adapt itself, setting its windings to a new transmission ratio, compensating this way the voltage level drop. The main types of tap changers are the DE-energized Tap Changer (DETC) which only operates while the PT is not loaded and the On Load Tap Changer (OLTC) which can operate when the PT is supplying the load [9, 11].

Bushings make the connection between the windings and the network through the PT's tank. They can bear very high voltages which is crucial since their malfunctioning could cause the PT to explode [9].

Insulating materials are materials that provide greater dielectric strength to the PT and they can be mineral oil, paper and pressboard. These materials cannot be replaced during the PT's lifetime so, once they reach the end of theirs, the PT's reaches its end as well.

2.2 Maintenance Policies Overview

It is believed that PTs' failures follow a bathtub curve pattern (Figure 2.2), where the first part represents premature failure, the second part represents a constant failure rate, and the third part, failure caused by PT's age [2].

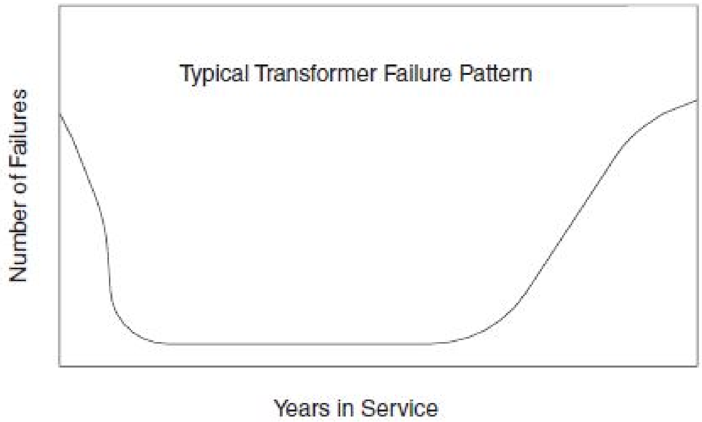

Figure 2.2: Bathtub failure curve [2]

Therefore, maintenance plans are extremely important to maximise the lifetime of a PT and minimise the risks that come with ageing (e.g. serious faults, failure). These plans assure that the device is working under the best conditions and that any faults are fixed promptly.

Although maintenance is extremely important, it is essential for companies to find a balance between maintenance and the costs that come with it because if maintenance activities are performed too frequently, it will have considerable costs although it will probably help improving PTs' condition. On the other hand, distant maintenance activities can also turn out to be expensive as it may be needed to repair unexpected faults that may have happened in the meantime. Therefore a balance between this two options would be the best option. Bearing this in mind, during the definition of a maintenance plan, a company may have several goals such as: to fix Pt's faults and prevent future ones, to improve their performance and to prolong their lifetime, all of these while keeping the costs to a minimum.

The following types of maintenance for PTs can be considered 2.3:

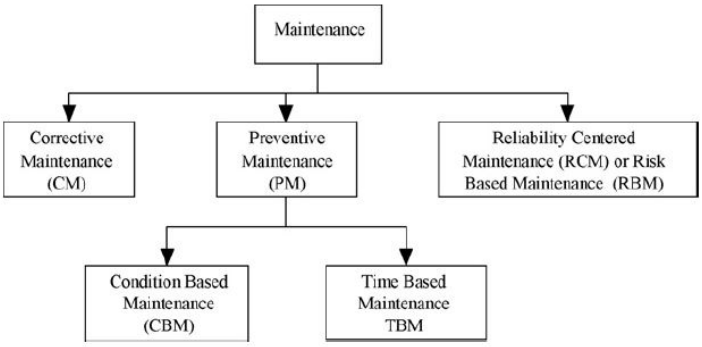

Figure 2.3: Different Types of Maintenance [3]

2.2.1 Corrective Maintenance (CM)

This type of maintenance is performed when failures occur. Therefore it is not commonly used and it is not a very recommended one since the continuous non detection of faults and non prevention can lead to serious failures that may cause the loss of the equipment and consequently, an interruption in the PG's service. [3].

Although this is a cheaper method since it avoids system interruption and has less costs with labour, it can become more expensive when failures occur considering that repairing costs may overcome the costs presented by a preventive maintenance. Besides, there is the risk that the failure could lead to irreversible damage to the PT [12].

2.2.2 Preventive Maintenance (PM)

As suggested by the name, the purpose of a PM is to prevent possible faults and extend a PT's lifetime to the most.

We may consider two types of Preventive Maintenance:

- **Time-Based Maintenance (TBM):** this maintenance is performed according to a schedule and so, inspections and maintenance are done on a periodic basis which helps to detect faults early and as a result prevent failures. Nevertheless, this does not guarantee that failures will not happen as they might occur between maintenance procedures.

  When planning maintenance interventions based on a time schedule, it is very important to find a balance between their frequency and their cost, because regular maintenance performed in short intervals may be very expensive and even unnecessary [3].

- **Condition Based Maintenance (CBM):** CBM is performed when CM detects a fault that is still in an early stage and can be treated. If that doesn't happen, said fault might evolve and turn into a more serious problem.

Despite this type of maintenance is only performed when incipient faults are detected, requiring, therefore, a smaller number of interventions, it requires constant monitoring of different parameters of the PT which can be rather expensive. [3]

2.2.3 Risk Based Maintenance (RBM):

RBM's can be considered a multi maintenance strategy method. Its main goal is to maintain a PT on its best condition with the minimum cost possible. To perform it, each fault's risk is measured so that maintenance actions can be the most adequate. The risk is calculated as the product between the probability of failure and consequences index 2.1.

$$Risk = P_{failure} \cdot C_{index} \tag{2.1}$$

When evaluating the existing failures it separates the ones with low risk from the ones with high risk. The ones with low risk are treated by low-cost methods (i.e. Corrective Maintenance). The ones with higher risk are treated by CMB or TBM methods, being the maintenance interval calculated based on the predicted cost [3].

2.3 Condition Monitoring

Nowadays, there are plenty of methods a company can use to monitor and understand what is the actual PT's condition. These methods vary on the standard procedure as well as in the variable they study. A few examples of these methods consist of oil testing (e.g. dissolved gas analysis (DGA) [8, 5, 13, 2, 4, 14], oil quality test ([8, 13, 2, 4, 15] and furfural content [8, 13, 2, 4]), paper insulation test (performed based on DGA and furfural content results) [6, 4], power factor testing [8, 2, 4], infrared thermography [2, 4], excitation current test [4], winding resistance, recovery voltage and internal temperature measurement [2], tap changer testing, load history and maintenance data [8, 13].

Although all these methods are important in its own way since all of them provide important information on PT's condition and are performed ind different ways, in this document only DGA, oil quality test, furfural content and paper insulation test will be covered due to its importance to the work developed.

2.3.1 Dissolved Gas Analysis (DGA)

DGA is a commonly used method to monitor a PT's condition [4]. Even though sometimes the information provided by this test is not enough to understand what a PT's condition is, it allows to detect some internal faults (e.g. overheating, partial discharge, overloading) [8, 13, 2]. In this test, the concentration of specific gases such as hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), ethane (C_2H_6), among others, is analysed which allows the maintenance manager to detect said faults. These gases formation occur due to oil (C_2H_6 and H_2) and insulation paper degradation (CO and CO_2) [2, 14].

Throughout time, multiple techniques of performing a DGA have been developed. A few examples of these techniques are the Key Gas Analysis (KGA) method, Roger's Ratio Method (RRM), Doernenburg Method, Duval Triangle Method (DTM) and Duval Pentagon Method (DPM) [8, 16, 4].

Due to the fact of being based on templates with standard concentration values, KGA is not the most accurate method. Its accuracy depends on the technician expertise since the measured values may not match the template ones but the problem still exist [4].

Although they are different, both RRM and Doernenburg Method get their conclusions based on $H_2, CH_4, C_2H_2, C_2H_4$ and C_2H_6 concentrations [4].

DTM and DPM are interconnected being DPM an improvement of DTM. DTM is a very accurate method capable of detecting a great number of faults. It is divided into 7 different fault regions (Figure FigureDuvalTriangle): PD (partial discharge), D1 (low energy discharges), D2 (high energy discharges), T1 (thermal faults up to 300^{o}C), T2 (thermal faults between 300 and 700^{o}C) and finally T3 (thermal faults greater than 700^{o}C).

In order to detect faults, points in the triangle must be discovered according to the analysed gases concentration. First, the percentage of CH_4 is taken and a line along that value and parallel to the base (C_2H_2 side) is plotted. Then the same procedure is done for the concentration of C_2H_4, only this time the line must be parallel to the left side (CH_4 side). Finally, the process is repeated for the concentration of C_2H_2 and the line must be parallel to the right side of the triangle (C_2H_4 side). By intercepting the three lines it is possible to get a single dot that provides information on possible existing faults in the PT [4].

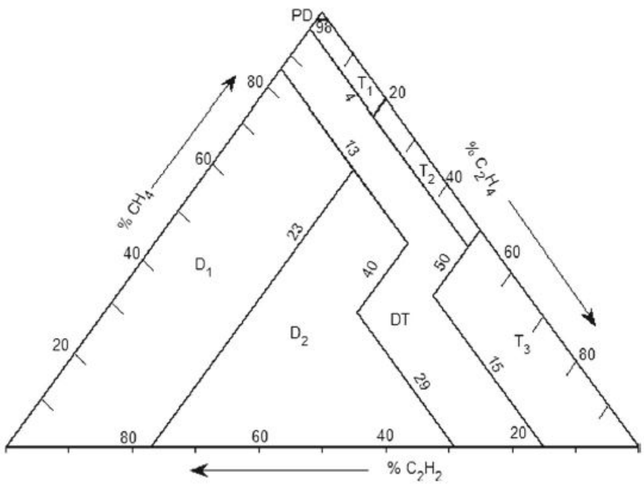

Figure 2.4: Duval Triangle Method [4]

DPM is a very similar method but it has the capacity of detecting more faults than DTM. Besides the 6 faults DTM can detect, DPM can detect four more specific faults. These specific faults are thermal faults T3-H in oil (T3-H), thermal faults from T1-C to T3-C (C), overheating with temperatures under 250°C (O) and stray gassing of mineral oil at 120 and 200°C in laboratory (S) [5]. An example of the DPM is represented below in Figure 2.5:

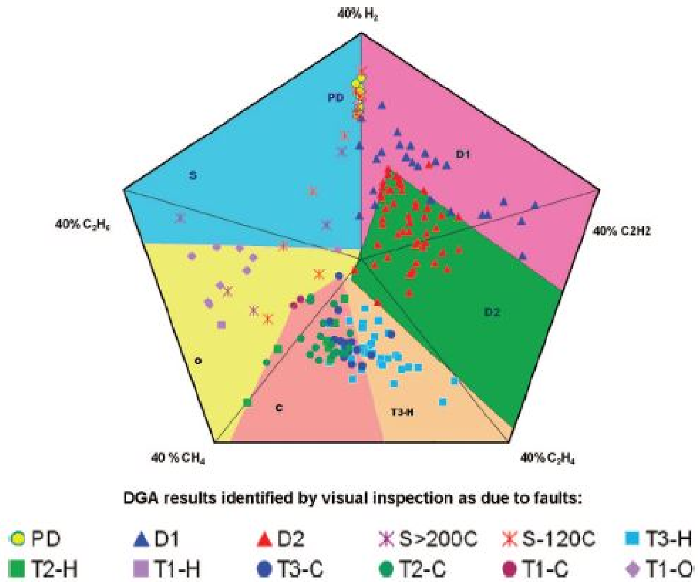

Figure 2.5: Duval Pentagon Method [5]

2.3.2 Oil Quality Test

Insulating oil is a very good indicator of the PT's actual condition. Nevertheless, throughout time insulating oil deteriorates and so it is important to replace it as doing so helps the PT to perform better and its lifetime might be extended [2, 4].

In order to evaluate the degree of insulating oil's deterioration, a set of tests is performed. This tests can be electrical, physical and chemical and their results are helpful in planning the PT's maintenance, avoiding this way, unpredictable faults and damages that might happen due to bad oil condition [2].

2.3.3 Furfural Content

Furfural is an organic compound that can be found in insulating oil due to insulating paper deterioration. Analysing its content in oil is of high importance because it provides very important information about paper insulation's condition which is crucial to the PT's well functioning.

Despite the fact that there are multiple furans that can be found in oil, the most significant one for this project is the 2-furaldehyde (2FAL) which has been proved to be linked with paper insulation degree of polymerization (DP). This will be explained in 2.3.4. It has been proven that the greater the 2FAL content, the smaller the degree of polymerization [13, 17, 18].

One of the major drawbacks of this method is that furfural contents lower significantly when the oil is changed, turning to approximately zero and so they stop providing real information on the paper condition [13, 17].

In this project, the content of 2FAL over time will be studied in order to predict an approximate EOL for a PT.

2.3.4 Paper Insulation

Paper insulation condition is probably the most important indicator of the remaining lifetime of a PT as it is not a replaceable part and so if it reaches the end of its useful life, it is very likely that the PT reaches it too [6].

As it ages, insulation paper loses its electrical and mechanical properties. As paper loses its properties it generates water and gases such as CO and CO_2 that are dissolved in oil. Therefore, to understand what the paper condition is, these generated products are studied in methods like furan analysis (as seen in 2.3.3), DP and CO_2/CO ratio [4].

DP decreases over paper insulation lifetime and it is considered that paper insulation has reached the end of its useful life when its DP reaches a value between 200 and 150 which, according to equation 2.2 is equivalent of a 2FAL content between 6.45 and 9.66 respectively.

Based on experimental data, formulas that estimate DP in order to 2FAL content (in mg/L or ppm) have been developed. One of the most commonly used is the Chendong equation and it was decided to use it on this thesis [19, 20]:

$$DP(2FAL) = \frac{1.51 - \log_{10}(2FAL)}{0.0035} \tag{2.2}$$

Which translates to the following plot (Figure 2.6):

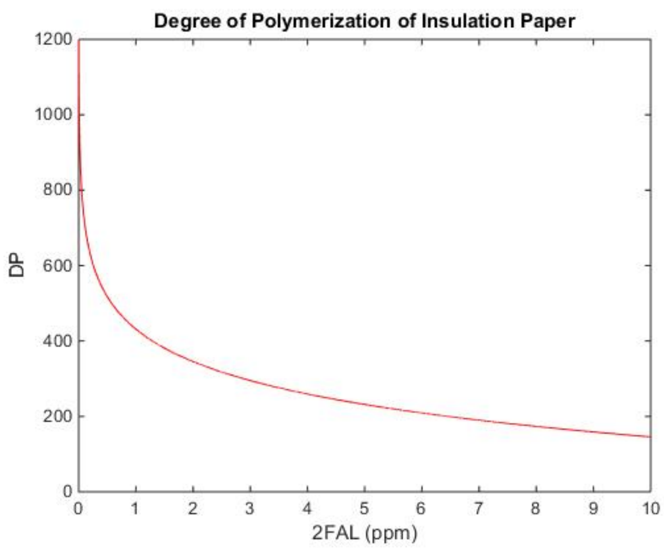

Figure 2.6: Degree of Polymerization

This equation will be used in this work to understand what's the current PT condition like and therefore, try to estimate its approximate time of EOL.

Another mentioned method to undersand insulation paper's condition is the CO_2/CO ratio. This test can provide information on existing faults (e.g. insulation exposure for $CO_2/CO > 10$). Although it can provide information on existing faults, this method should be complemented with additional DP or furan analysis as it can provide false information considering that these two gases, are produced due to paper insulation overheating, but can also be produced due to oil decomposition [4].

2.4 Health Index

All of the methods mentioned in 2.3 can help to determine a devices health index.

Health index is the value which provides information about a device's condition making it easier to understand if it is ageing as it should or if it is deteriorating faster or slower than expected. Their condition is normally evaluated as Very Good, Good, Fair, Poor or Very Poor [13].

Once known the health index of a device it is easier to estimate its remaining lifetime and probability of failure [13].

Different methods of measuring PT's Insulation Paper condition and therefore estimate their Health Index and their EOL have been developed such as fuzzy logic methods [21, 22, 23], artificial neural network methods [24] and scoring maintenance methods [8].

Chapter 3

Challenge and Proposed Solution

The aim of this chapter is to present the challenge of this project and the different procedures that were adopted during its development. At the end of this chapter, the most relevant strategy will be presented and explained in detail.

3.1 The Challenge

As already mentioned in Chapter 1, the main goal of this project is to determine an approximate time for PT's EOL by studying the DP of paper insulation using the concentration of 2FAL over time. This estimate allows maintenance managers to know when a PT enters a risk zone. It does not mean that the PT will reach its lifetime end at the estimated age, but it means that, from that point on, it is at risk of failing at any moment. As already mentioned in subchapter 2.3.3, one of the most drawbacks of performing a study based on 2FAL concentration, is that it drops when the oil is changed, making it impossible to get a real DP measure. So in this project, the challenge was to understand how 2FAL content varies over time, understanding how the DP varies. This way it would be possible to estimate a PT's EOL.

3.2 Dataset Description

In order to understand how 2FAL varies over time and consequently discover how DP varies, it was necessary to analyse real data which was provided. This data contained different parameters such as DGA analysis ($CO, CO_2, H_2, CH_4, C_2H_4, C_2H_6$ and C_2H_2 content), 2FAL content, date of analysis, PT's code, location, year of fabrication, oil temperature and acidity level although not all of this data was used.

In Table 3.1, descriptive statistics regarding the analysed data are presented.

Table 3.1: Descriptive Statistics On Analysed Data

Number of power transformers	922
Average age at the time of the first register	16,55 Years Old
Average age at the time of the last register	27,01 Years Old
Average number of 2FAL samples per power transformer	10,3926

3.3 Adopted Procedures

The initial procedure was to filter the useful parameters from the remaining data. As a result, a file was created containing the PT's code, year of fabrication, date of oil analysis and 2FAL content at that time. Using this information, other parameters were calculated such as PT's age, PT's DP at the time of each sample, among others. In order to perform a quick analysis of the raw data, a 2FAL according to age graph was plotted. The results are presented below in Figure 3.1.

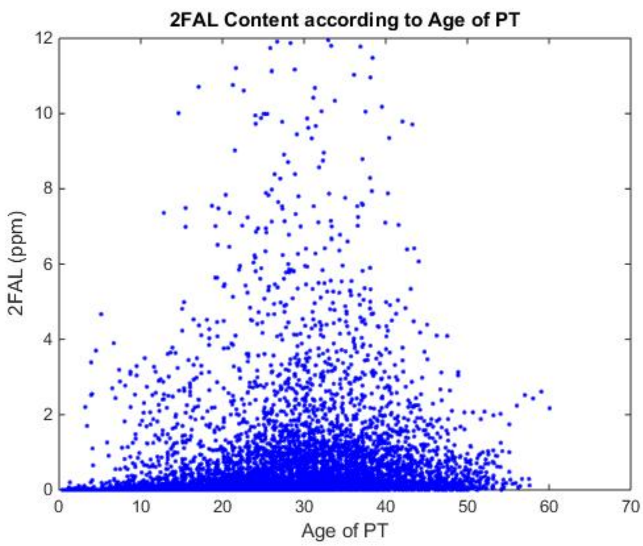

Figure 3.1: 2FAL content according to PT's age

By looking at Figure 3.1 it is difficult to draw any conclusions, specially due to the high number of registers between 0ppm and 2ppm over time. This measures may be justified by the fact that every time an oil change happens, 2FAL content drops sharply.

In order to have a simpler vision of how 2FAL content evolves over time, average 2FAL content per age was calculated. It should be noted that this calculation does not take into account oil changes, being a simple average of the raw data. The results are plotted in Figure 3.2.

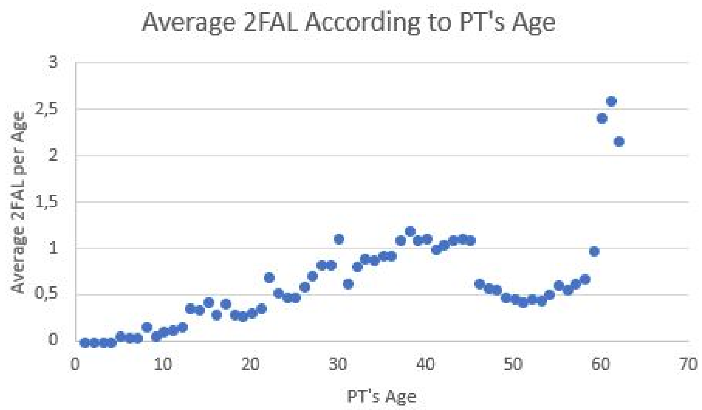

Figure 3.2: Average 2FAL content according to PT's age

As it is possible to observe in Figure 3.1, there is a great number of measures with low values (under 2ppm) for almost every age. This could have multiple explanations such as oil changes and transformers which measures were only registered at significant ages (over 20 years in some cases). These values distribution make it almost impossible to get any conclusions. With that in mind, and considering that there is not a specific register saying there was an oil change, the next step was to create a filter that would detect oil changes by detecting significant 2FAL drops.

Considering that every time the oil is changed, 2FAL values should drop to near zero but still having in mind that registered oil analysis could not match with the time of change, the adopted criteria was that an oil change had happened if the current measure was less than $\alpha\%$ of the previous record and that the previous record was greater than βppm as explained by equation 3.1:

$$Oil \quad Change: \quad 2FAL_i < 2FAL_{i-1} \cdot \alpha, \quad 2FAL_{i-1} > \beta \tag{3.1}$$

Besides detecting oil changes and distinguish them from outliers, the main goal of applying this filter is to make possible the understanding of 2FAL content variance over time. Therefore, every time an oil change is detected, 2FAL values are adjusted according to the last measure before the change (e.g. if measured $2FAL_{i-1} = 2.44$ and measured $2FAL_i = 0.03$, an oil change is detected and so real $2FAL_j = 2.47$, i.e. 2.44+0.03, for $j = i$).

An example of an oil change detection can be seen in Figure 3.3 where 2FAL measures for one particular PT are presented.

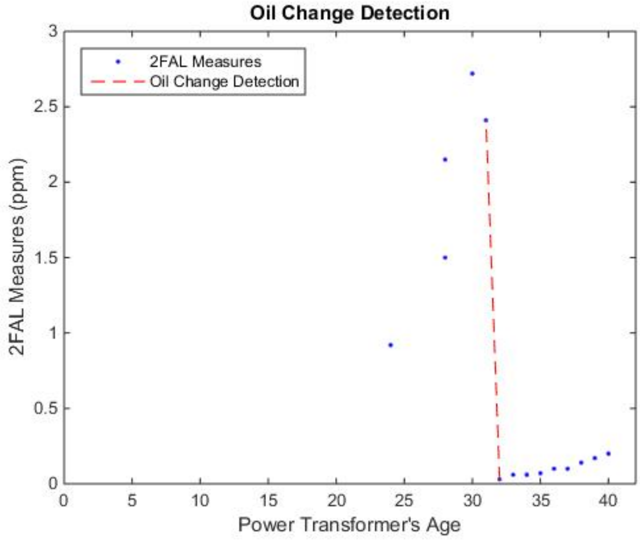

Figure 3.3: Detection of an Oil Change through 2FAL measurement analysis

After performing the adjustment to all 2FAL measures, considering $\alpha = 30\%$ and β=0.075ppm, the plot of average 2FAL adjusted values is represented in Figure 3.4. These values are also compared with the measured values represented in Figure 3.2.

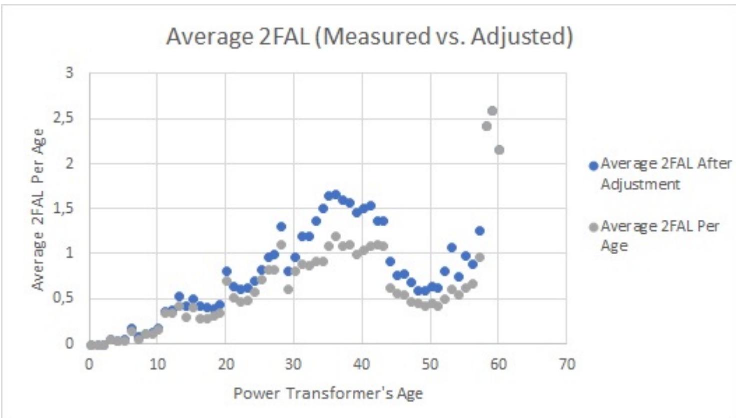

Figure 3.4: Average 2FAL content according to PT's age after adjustment

With the intent of getting a relationship between PT's age and the concentration of 2FAL, a regression was performed. It was decided to perform an exponential regression based on how the adjusted average values seem to evolve and based on literature review [17]. The result is the following equation (3.2) and it is represented in Figure 3.5.

$$2FAL = e^{0.01722 \cdot age} - 1 \tag{3.2}$$

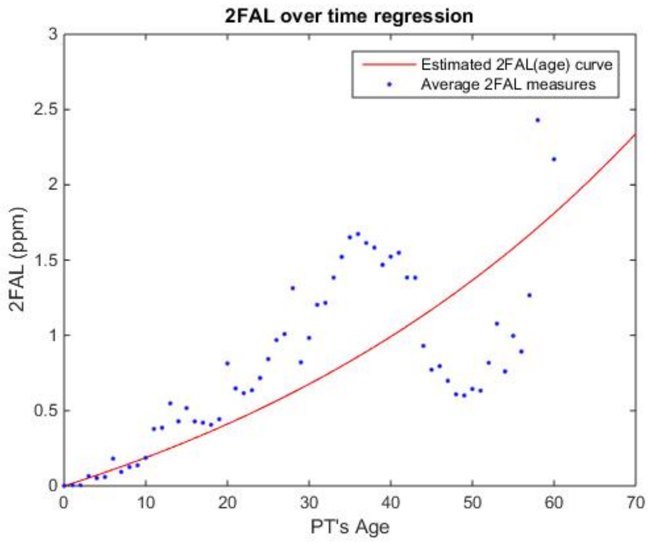

Figure 3.5: Regression of a 2FAL(age) curve

Taking into account the values of 2FAL needed for a PT to reach its EOL (subsection 2.3.4), and that the average lifetime of a power transformer is about 40 years [25], it is easy to understand that even at greater ages the values represented in Figure 3.5 are too low. Also, when compared to the 2FAL(age) function obtained in [17] (Equation (3.3) and Figure 3.6), the estimated function (3.2) is not reasonable to use.

$$2FAL = \frac{20.617 \cdot e^{0.0989 \cdot x}}{1000} \tag{3.3}$$

This situation can be justified by the fact that a significant amount of PTs only have their first measures at advanced ages, making it impossible to adjust their measures until the first registered oil change. This makes the average value of 2FAL much lower than it should be.

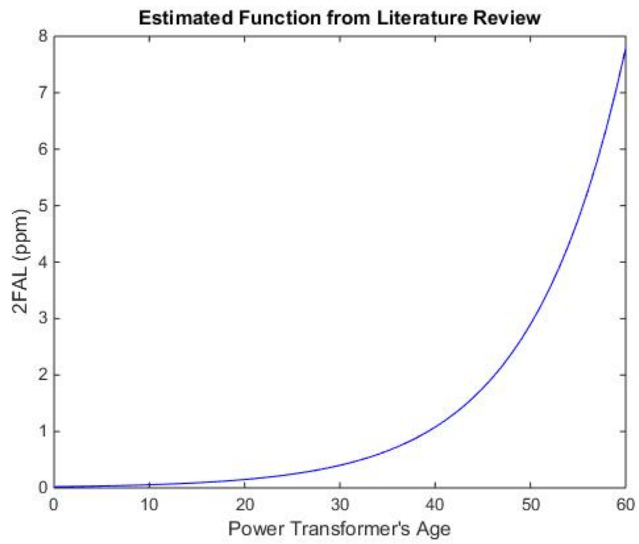

Figure 3.6: 2FAL(age) function in Literature Review

Considering that the average values could affect the results, it was decided to perform a regression using all measures. After some research, the use of the Least Squares Method seemed the most appropriate, but once again, the results were not promising as it is shown in Figure 3.7. In this case the obtained function is represented by equation (3.4).

$$2FAL = 0.6906 \cdot e^{0.0188 \cdot x} \tag{3.4}$$

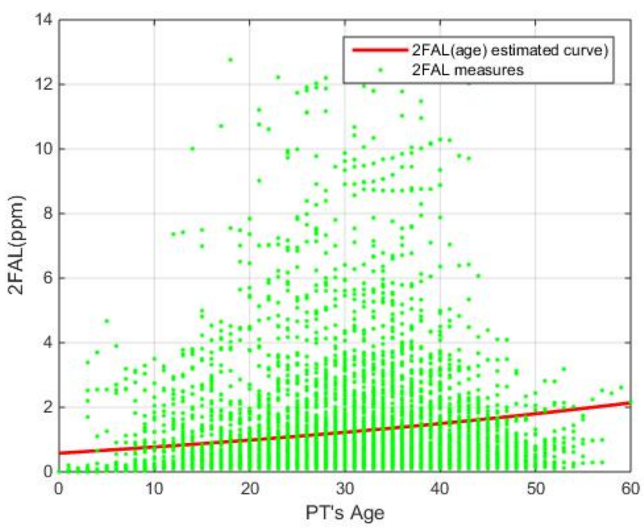

Figure 3.7: Result of a Least Square Method regression

3.4 The main Procedure

Bearing in mind that different kinds of approaches had been taken with none of them providing the expected results, and that a significant amount of data was affecting the study with no reference values to help eliminate them, it was decided to use an equation 3.5 developed by INESC TEC that relates DP with time. This curve was developed based on literature review and experimental studies [8, 26, 27, 28, 29].

$$DP(age) = DP_0 \cdot e^{\frac{-age}{k}} \tag{3.5}$$

In Equation 3.5, $DP_0 = 1200$ and $k = 32.3591$. This equation's curve (Figure 3.8) is similar to DP(2FAL) curve and it turned out to be crucial for this thesis' main goal.

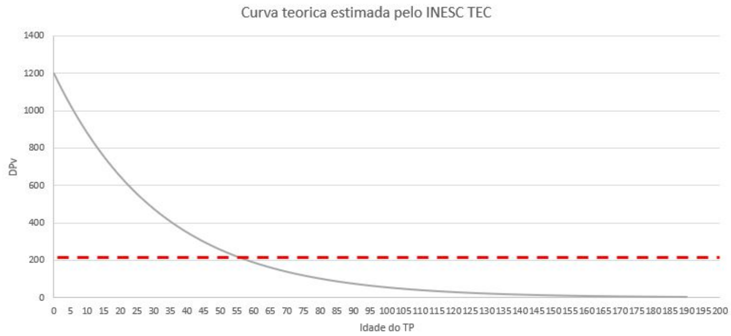

Figure 3.8: PT's DP according to its age (equation 3.5)

Once knowing the equation of this curve, the following function (equation 3.6) was developed to determine an estimate EOL for PT's that have suffered one or more oil changes.

Being n, the number of oil changes, $change_i$ the age at the time of oil changing i, DP_0 the initial value of DP (=1200), and ΔDP_i the difference of DP registered after an oil change i. Depending on the DP measured values, k may vary. If these values are according to the DP(age) curve, k=32.3591, otherwise a regression will be performed to find a curve that best fits DP measures, depending k on such regression.

$$DP(age) = \begin{cases} \mathrm{DP}_0 \cdot e^{\frac{-age}{k}} & ,if \;\; age < change_1 \\ (\mathrm{DP}_0 + \sum_{i=1}^{n} \Delta\mathrm{DP}_i) \cdot e^{\frac{-age}{k}} & ,if \;\; change_n \leq age < change_{n+1} \end{cases}$$

(3.6)

After knowing the DP values for every age with oil changes taken into account, when estimating the EOL, $\sum_{i=1}^{n} \Delta\mathrm{DP}_i$ is subtracted from the curve expression in order to get a real DP value and this equation is equalled to 200 (DP value for EOL), as demonstrated in Equation 3.7.

$$DP(age) = (DP_0 + \sum_{i=1}^{n} \Delta DP_i) \cdot e^{\frac{-age}{k}} - (\sum_{i=1}^{n} \Delta DP_i) \tag{3.7}$$

Besides the mathematical formula, an algorithm was developed and will be explained in detail in chapter 4.

Chapter 4

Implementation

This chapter aims to present and explain the developed algorithm. In section 4.1 a flowchart explaining the code is presented and in the following subsections, an insight on how the algorithm works step by step is provided.

The presented algorithm was developed using Matlab since it is a friendly user software with a significant performance in data analysis.

4.1 Algorithm

Aiming to ease the understanding of how the algorithm works when trying to estimate a PT's EOL, a simplified flowchart of the algorithm is presented in Figure 4.1. The first step is to import the data the user wants to study since it is not commonly provided in this file format. Once this step is concluded, the algorithm starts to filter and adjusting data according to the specified restrictions, including, deleting PTs which have all measures as zero. After filtering all the data the algorithm the algorithm is then ready to estimate PTs' EOL. In order to better understand this algorithm, each step will be detailed throughout sections 4.1.1, 4.1.2 and 4.1.3.

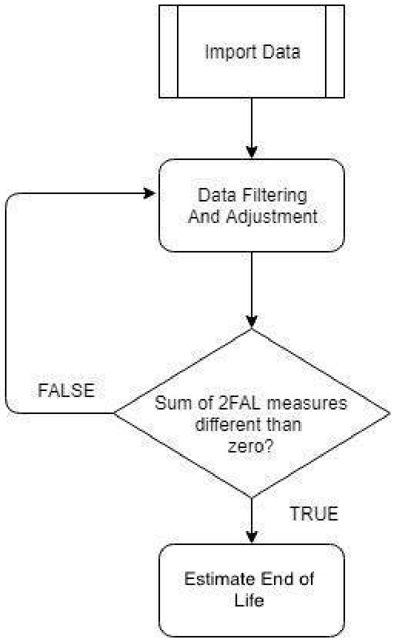

Figure 4.1: Simplified algorithm to estimate PT's End of Life

4.1.1 Importing Data

The first thing done by the algorithm is to import the data. It imports data from a .xls file (Excel sheet), putting the entire data in a matrix. In this case, the imported data was previously filtered in Excel, only being imported relevant parameters for this project (e.g.: age, 2FAL, DP, among others). From this point on, all of the modifications that may be done, are applied to the created matrix.

4.1.2 Data Filtering and Adjustment

When filtering and adjusting data, there are two main steps to perform. The first one is to delete 2FAL values that are considered too high and so, could be tampering the data sample. In this case, the chosen filter value was 12ppm which is equivalent to a DP of approximately 123. As a result, all 2FAL values higher than 12ppm were eliminated.

The reason this filter was adopted was due to the fact of some 2FAL measures presenting values that would mean a DP around 0 or even negative, which, theoretically is impossible. In Figure 4.2, a simple flowchart explains how the filter works.

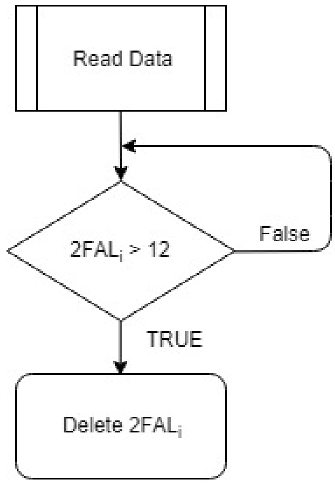

Figure 4.2: Simplified algorithm of Deleting Values That Are Too High

After deleting all the outlier values, the next step is to detect if a transformer has suffered oil changes or not. Thus, the first step is to make sure that only the data of the same PT is compared ($PT_i = PT_{i-1}$) and then apply the criteria of an oil change to 2FAL data already mentioned in chapter 3 section 3.3. This criterion is explained in Figure 4.3. If it is met, then an oil Change is detected. Otherwise, the drop is simply an outlier.

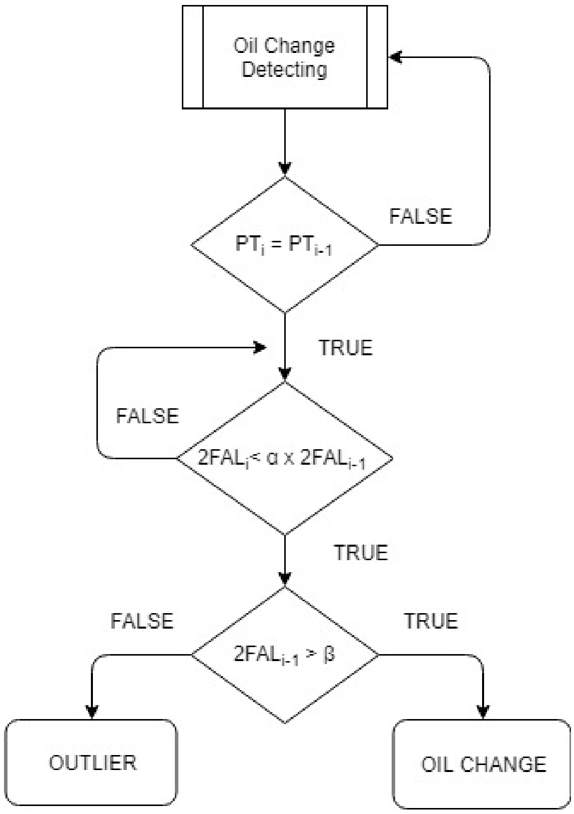

Figure 4.3: Algorithm for Detect Oil Changes

4.1.3 Estimating Power Transformer's End of Life

This is the most complex part of the algorithm and it is presented in Figure 4.4. In this step, PT's are separated into two categories. The first one, PT's that have no oil changes detected. And the second one, PT's that have one or more oil changes detected.

The first thing to do for both groups is to plot data for each PT individually (for PT's belonging to the second group their data will be separated in groups according to the time they belong, i.e. before the first oil change, after the first change and before the second change, and so on). After that, the Deviation (D) (equation 4.1) and Absolute Deviation (AD) (equation 4.2) of DP values (calculated through 2FAL measures) compared to the DP(age) curve (equation 3.5) will be calculated.

$$D = \sum_{i=1}^{n} (y_i - \hat{y}_i) \tag{4.1}$$

$$AD = \sum_{i=1}^{n} |y_i - \hat{y}_i| \tag{4.2}$$

Now, for PTs with no oil changes, D/AD is calculated. If its value is near zero, then we estimate the EOL through the equation 3.5. Otherwise, we perform a regression to find the curve that better fits the PT's data and then, estimate it according to the new curve.

For PTs with one or more oil changes, the process is similar, but we repeat the first step for N+1 times (being N the number of oil changes) and each time, if D/AD is not approximately zero a regression will be performed and with the expression obtained at the last period, EOL is estimated. Performing a regression for each period is extremely important to guarantee that we are using the curve that best fits the PT's ageing.

For this group of PTs is important not to forget that, at every oil change, DP increases and so it is necessary to adjust the curve (ΔDP) and this value should be updated, everytime that a new oil change happens. When estimating the EOL, (ΔDP) should be subtracted from the obtained curve expression in order to understand what point of that curve, would be equivalent to DP = 200 at the original curve.

The algorithm explained above is represented in Figure 4.4.

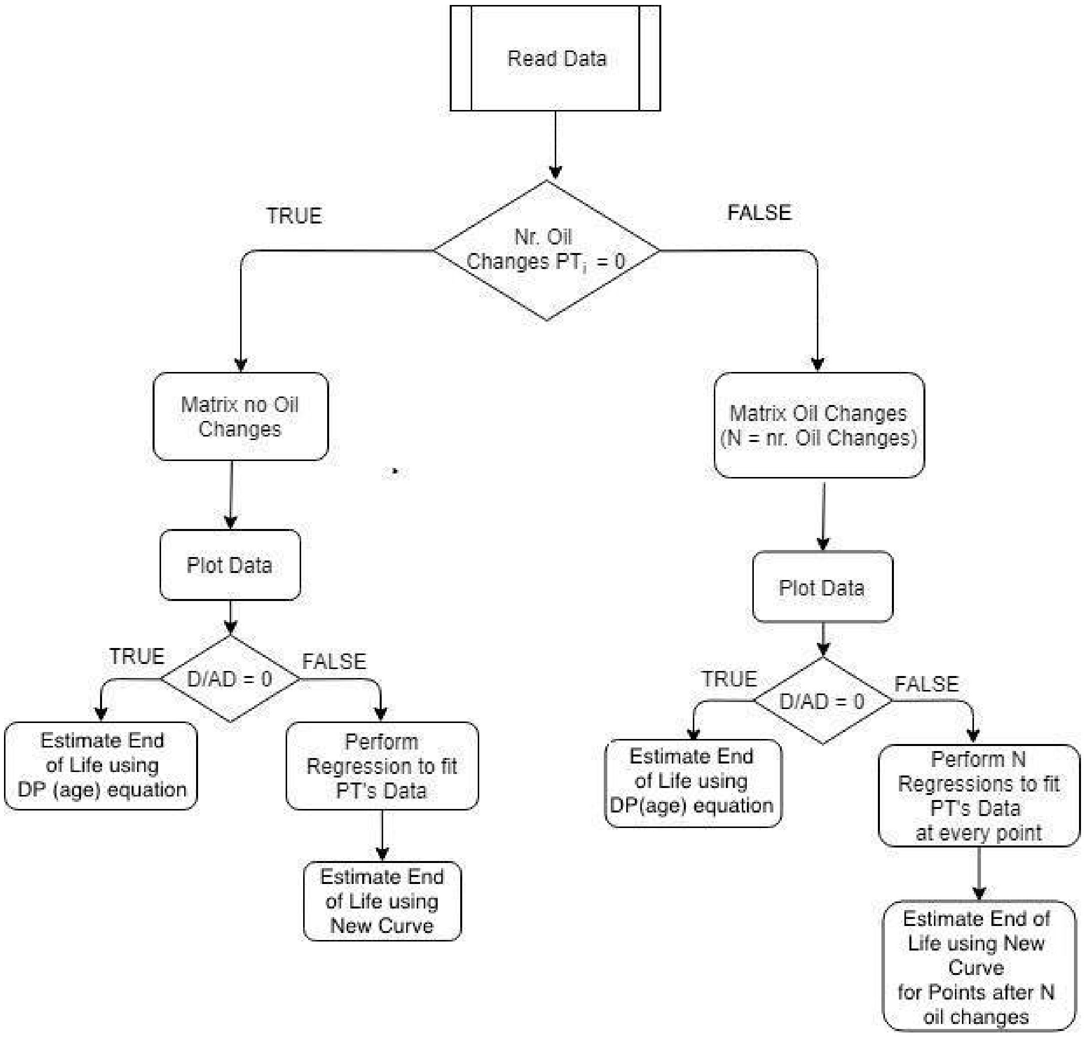

Figure 4.4: Algorithm for Estimating End of Life

Chapter 5

Tests And Results

In this chapter, the tests executed for validating the developed methodology are presented. These tests were performed using the created Matlab algorithm and with real data.

Although tests were performed in a large amount of PTs, only a few will be represented, in order to demonstrate all possible conditions.

5.1 Results

When estimating a PT EOL, different conditions can be faced. It could be a PT that is barely new and has not suffered any oil changes, one that has suffered one or even more oil changes but with all data registered correctly, or even one that only has registered data since its middle age (e.g. 20 years old). Therefore, tests performed in the described conditions will be performed. However, before performing these tests, a sensitivity analysis for α and β values was performed. In Table 5.1, three values for each variable were studied being the total number of detected oil changes compared for each combination. In Figure 5.1, all the combinations are compared in a plot.

Table 5.1: Sensitivity analysis for α and β

α	β	**Total Number Of Oil Changes**
0,3	0,05	358
0,3	0,075	319
0,3	0,1	282
0,4	0,05	413
0,4	0,075	375
0,4	0,1	323
0,5	0,05	457
0,5	0,075	410
0,5	0,1	362

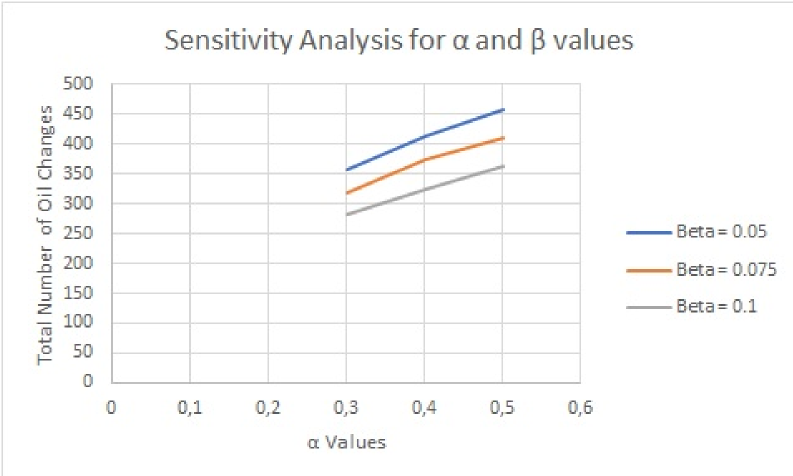

Figure 5.1: Sensitivity analysis for α and β

After comparing the results of the analysis, it is possible to see that the number of oil changes increases for bigger values of α and smaller values of β. Considering this observation, it was decided to perform tests using α and β values of 30% and 0.075ppm respectively.

5.1.1 Power Transformers with no oil changes registered

The first PT tested has no oil changes registered and its records start at 9 years old. In this case, D/AD was very close to zero so the original DP(age) curve (3.5) was used to estimate this PT's EOL. Considering that it will keep working under normal conditions and that no unexpected faults occur, it is expected that this PT enters its risk zone at approximately 58 years old (Figure 5.2).

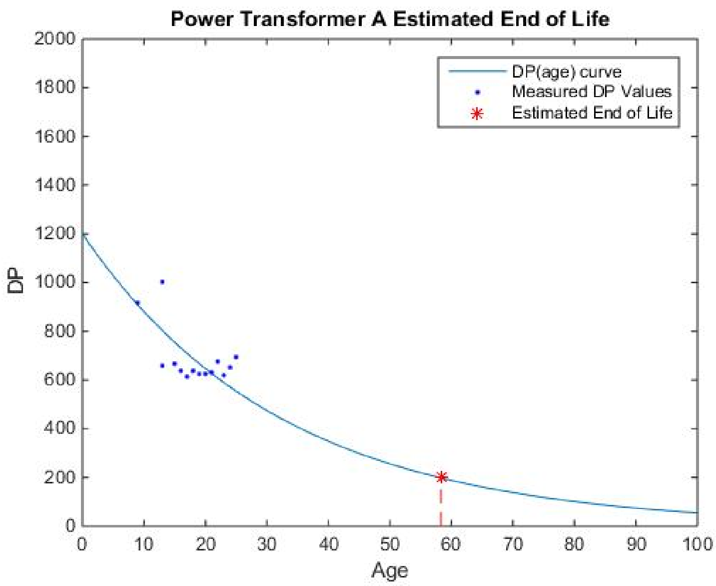

Figure 5.2: Estimated End of Life for PT A

A different scenario occurred when testing a different PT. This PT's DP values were much lower than they should be so it was necessary to estimate a new curve, that would fit this PT better. After estimating the curve the EOL was estimated at the age of 36 (Figure 5.3).

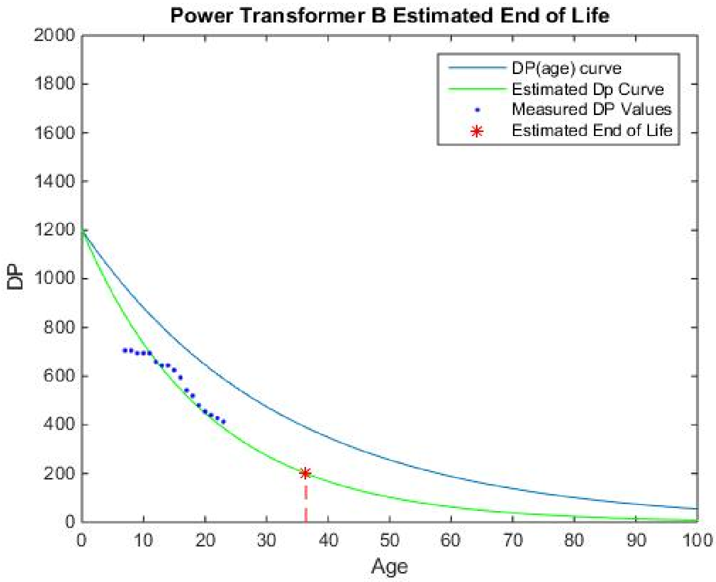

Figure 5.3: Estimated End of Life for PT B

PTs C (Figure 5.4) and D (Figure 5.5) are two examples of PTs that have no oil change registered and that data registries after they were twenty years old. However, unlike PT D, PT C did need a new curve estimated to determine its EOL.

In both of this cases, it is very likely that the estimated EOL comes with a significant error due to the fact that previous measures and possible previous oil changes are unknown which directly affects the EOL calculation. More specifically, if an oil change is not registered, the ΔDP is not being taken in consideration which will probably cause the remaining lifetime estimation to be greater than it should.

In this case an EOL at 96 years old for PT C and at 58 years old for PT D.

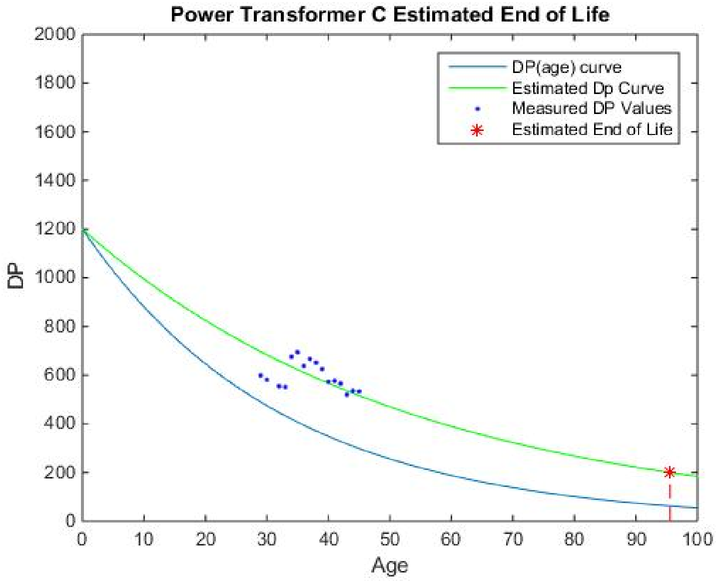

Figure 5.4: Estimated End of Life for PT C

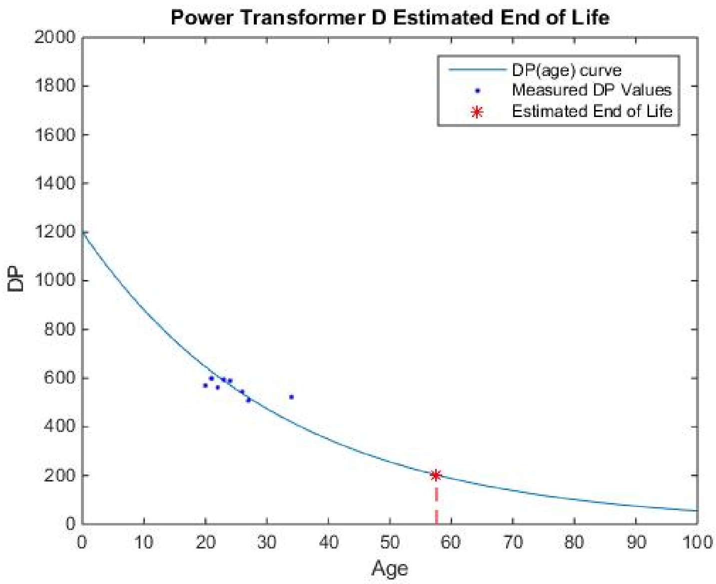

Figure 5.5: Estimated End of Life for PT D

5.1.2 Power Transformers with one or more oil changes registered

The first test performed in a PT that has registered one or more oil changes was in PT E (Figure 5.6). This PT shows how important early registries are in estimating an EOL. As it is possible to see, it has registries since it was 7 years old and an oil change is registered at 9 years old which makes the estimated EOL to be much earlier than in other examples seen (e.g. PT C). In this case, it is estimated that PT E reaches its risk zone at 23 years old. Once again it is important to bear in mind that this estimate is made assuming the PT will keep work under normal conditions and will keep ageing as it has been so far. This estimate will probably change if maintenance are performed (DP will be higher again) or even if unpredictable faults occur (DP will probably be lower).

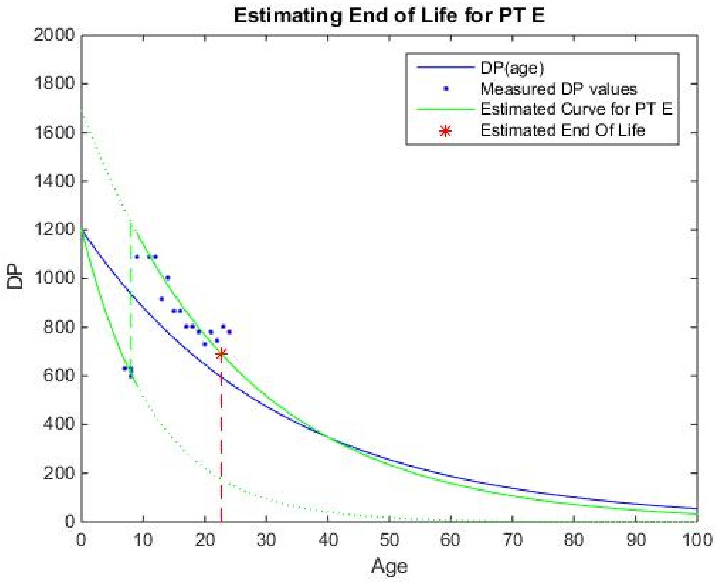

Figure 5.6: Estimated End of Life for PT E

Next, a test was performed using data from PT F (Figure 5.7). Here, a curve regression was needed both before and after the oil change and it is clear from the obtained curves that this PT was ageing faster than it was supposed to, which explain the estimated EOL at 20 years old.

An important detail to outstand in this test is that there are five DP measures even after the estimated EOL. This means that although the PT was still operating, it was at imminent risk of failure and so its replacement should probably be considered.

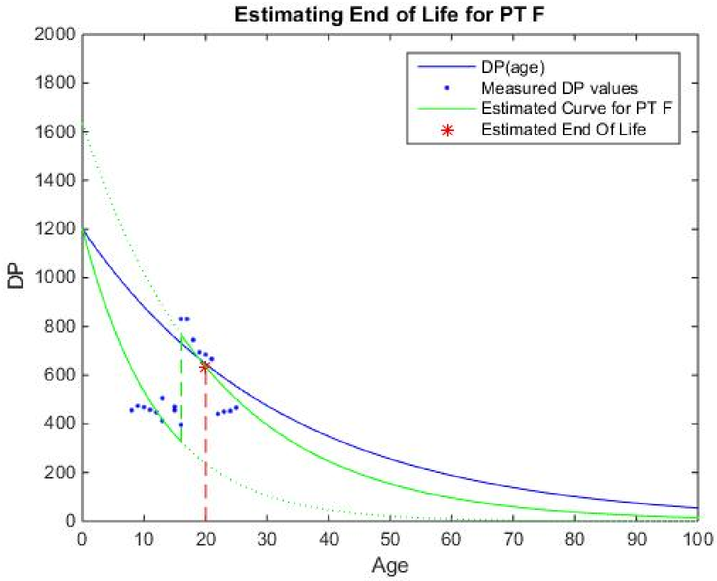

Figure 5.7: Estimated End of Life for PT F

Finally, tests in transformers with two oil changes were performed. In all of the performed tests, new estimated curves were needed. The tested PTs were G, H, I and J.

PTs G (Figure 5.8) and H (Figure 5.9) got satisfactory results with an estimated EOL at 27 and 37 years old respectively both of them without any DP measures after the estimated value.

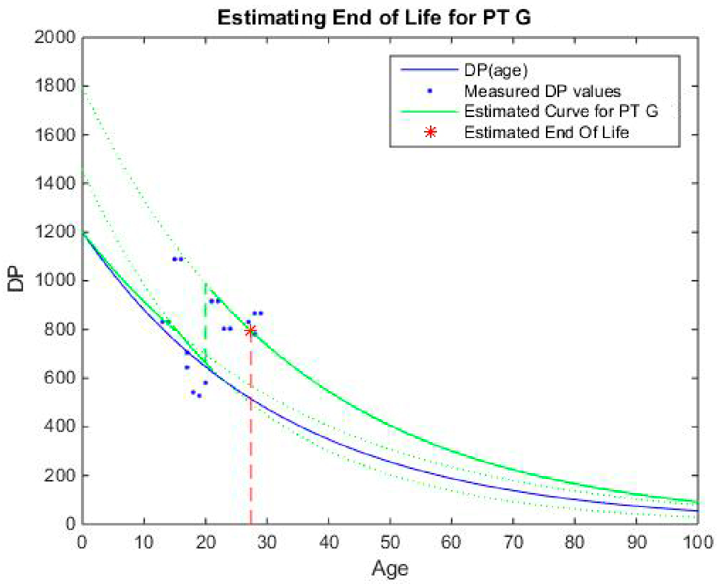

Figure 5.8: Estimated End of Life for PT G

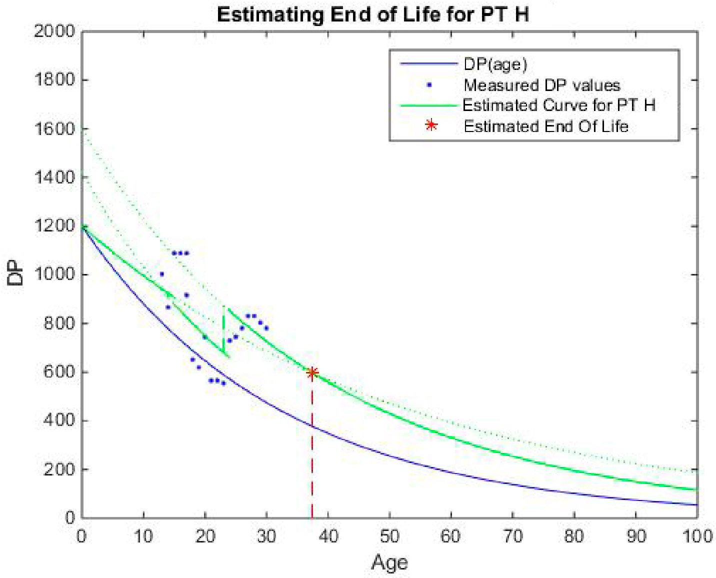

Figure 5.9: Estimated End of Life for PT H

However, when testing PTs I (Figure 5.10) and J (Figure 5.11), the system did not provide a satisfactory result. Because it considers the cumulative ΔDP, in both cases it provides a very premature EOL. For PT I, the EOL was at 29 years old, 17 years before the last DP measure registered and for PT J it was at 36 years old, 21 years before the last DP measure registered. However, in both cases, records did not exist until the PTs were between twenty and thirty years old which may justify the obtained results.

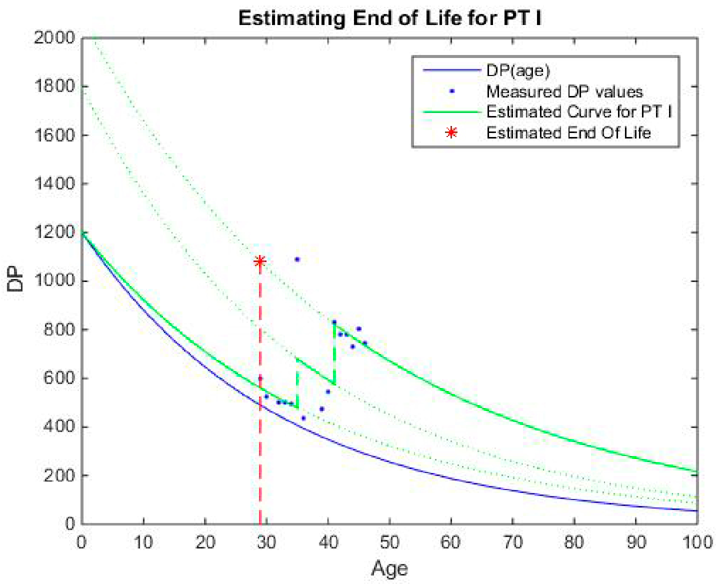

Figure 5.10: Estimated End of Life for PT I

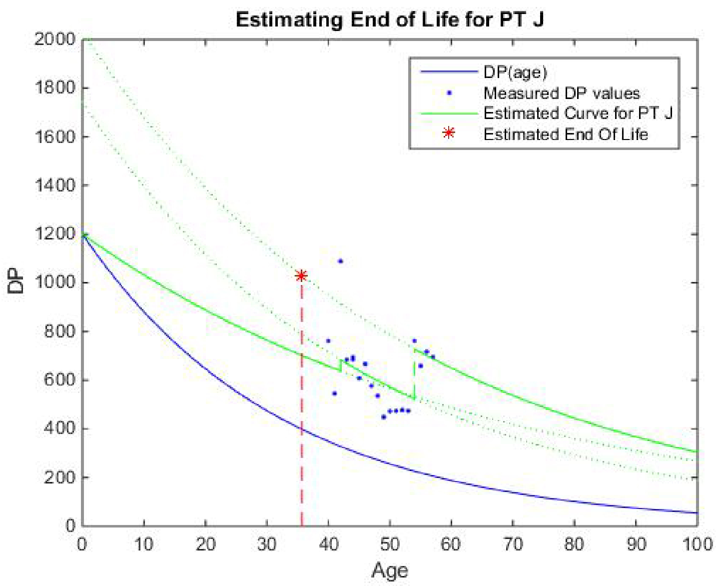

Figure 5.11: Estimated End of Life for PT J

Chapter 6

Conclusions and Future Work

In this final chapter, a discussion regarding the obtained results, as well as a reflection on the work developed and future work suggestions, based on the work that was done, are presented.

6.1 Results Discussion

As it was demonstrated in 5.1, the developed algorithm estimates a PT's EOL having the ability of detecting oil changes and performing an adequate estimate, according to the PT's situation. It is very important to understand if the evaluated PT is ageing according to the theoretical expression (3.6) or, if it is necessary to estimate a new expression for such PT which helps getting a more accurate result. This happens because if we were to use the theoretical expression for every case and if for example we were dealing with a transformer that is ageing faster than expected, it would probably reach the end of life at an earlier age than the estimated.

The developed methodology has proved itself more accurate than methods that do not consider oil changes when studying 2FAL content in oil. For every studied PT, if oil changes would not be taken into account, the EOL would be at a much older age than it actually was since the measured DP at that time would not match the real DP.

When considering oil changes, this method provides a more accurate estimation of the real DP value since it considers previous measures of 2FAL and so it normally considers higher values of 2FAL than the measured ones. For that reason, its estimate of the PT's EOL becomes more accurate as well. This methods accuracy will be possible to evaluate when information on the studied PTs EOL becomes available.

It is important to consider that this method's precision can be affected by the existing data or lack of it. Therefore, to guarantee a good estimate, it is crucial that registers are made since early ages so it can be possible to efficiently determine the EOL. It is also extremely important that oil samples are taken frequently, at least once a year so it is possible to understand 2FAL's (and consequently DP's) behaviour and more accurately estimate PTs' EOL.

6.2 Reflection on the thesis

PT lifetime estimation is a challenging activity and nowadays, there are no methods that can do it 100% effectively, especially because there are many variables to consider, some of which are out of anyone's control (e.g. unpredictable faults). Therefore, the only viable solution is to monitor PT's behaviour and perform an adequate maintenance on a regular basis. By doing so, a PT lifetime will be longer and it becomes easier to estimate its EOL.

In this project, 2FAL measures were used to determine when oil changes had happened and to estimate the DP value at the time of each measure. Knowing the real DP at each measure, these were compared with the expected values of DP calculated through 3.5 and if necessary, a new curve that would best fit DP measures would be estimated. Finally, and based on the most adequate curve, the EOL would be estimated and as shown in 5.1 it was possible to do it, and so, this project's main goal was accomplished.

6.3 Future Work

Although the objectives outlined for this project were answered, it is not possible to evaluate they are answered effectively as there is lack information about the age at which the PTs used in this studied, reached their end of life. However, it would be interesting to study different ways of filtering data, i.e. detecting oil changes.

For example, it would be interesting to detect oil changes by studying the oil acidity level, combined with 2FAL levels as well as to develop an algorithm that would provide investment decisions, based on the EOL. Another interesting possibility would be the development of an artificial neural network that would frequently update its estimate and provide maintenance suggestions.

References

[1] Ronny Fritsche, Siemens Ag, Sector Energy, and T T R Pn. Siemens Energy Optimises Power Transformers with the Aid of 3D EM Simulation. pages 3–6, 2009.

[2] M Wang, A.J. Vandermaar, and K.D. Srivastava. Review of condition assessment of power transformers in service. *IEEE Electrical Insulation Magazine*, 18(6):12–25, 2002.

[3] Ahmed E.B. Abu-Elanien and M. M.A. Salama. Asset management techniques for transformers. *Electric Power Systems Research*, 80(4):456–464, 2010.

[4] Md Mominul Islam, Gareth Lee, and Sujeewa Nilendra Hettiwatte. A review of condition monitoring techniques and diagnostic tests for lifetime estimation of power transformers. *Electrical Engineering*, pages 1–25, 2017.

[5] Michel Duval and Laurent Lamarre. The Duval Pentagon — A New Complementary Tool for the Interpretation of Dissilved Gas Analysis in Transformers. *IEEE Electrical Insulation Magazine*, 30(6):1–4, 2014.

[6] Bogdan Gorgan, Petru V. Notingher, Jos M. Wetzer, Harry F.A. Verhaart, Peter A.A.F. Wouters, Arjan Van Schijndel, and Gabriel Tanasescu. Calculation of the remaining lifetime of power transformers paper insulation. *In Proceedings of the International Conference on Optimisation of Electrical and Electronic Equipment, OPTIM*, pages 293–300, 2012.

[7] I Höhlein, A J Kachler, S Tenbohlen, and T Leibfried. Contribution for CIGRE SC12 / A2 - Merida - Kolloquium Transformer Life Management German Experience with Condition Assessment State of Art of Diagnostic. pages 1–13, 2003.

[8] A. Naderian, S. Cress, R. Piercy, F. Wang, and J. Service. An Approach to Determine the Health Index of Power Transformers. *Conference Record of the 2008 IEEE International Symposium on Electrical Insulation*, pages 192–196, 2008.

[9] Jean Sanchez and Mladen Banovic. Basics of Power Transformers. *Transformers Magazine*, 1:22–25, 2013.

[10] N Dominelli. Equipment health rating of power transformers. *In Conference Record of the 2004 IEEE International Symposium on Electrical Insulation*, (September):163–168, 2004.

[11] Dieter Dohnal. On-load tap changers for power transformers. *MR Knowledge Base*, page 24, 2013.

[12] Stephen D. Smith. Periodic testing and maintenance of power transformers to extend life and improve reliability. *In EIC 1977 - Proceedings of the 13th Electrical/Electronics Insulation Conference*, pages 156–158, 2016.

[13] a. Jahromi, R. Piercy, S. Cress, J. Service, and W. Fan. An approach to power transformer asset management using health index. *IEEE Electrical insulation magazine*, Vol.25(No.2):2, 2009.

[14] Norazhar Abu Bakar, A. Abu-Siada, Huize Cui, and Shengtao Li. Improvement of DGA interpretation using scoring index method. *In ICEMPE 2017 - 1st International Conference on Electrical Materials and Power Equipment*, pages 502–506, 2017.

[15] P.A. von Guggenberg and J.R. Melcher. An immersible relative saturation moisture sensor with application to transformer oil. *In Proceedings of the 3rd International Conference on IEEE Properties and Applications of Dielectric Materials*, pages 8–11, 1991.

[16] Diaa Eldin A Mansour. Development of a new graphical technique for dissolved gas analysis in power transformers based on the five combustible gases. *IEEE Transactions on Dielectrics and Electrical Insulation*, 22(5):2507–2512, 2015.

[17] Ir Mohd and Faris Ariffin. Paper 0784 Estimating The Age of Paper Insulation in 33 / 11 KV Distribution Power Degradation By-Products. *In 19th International Conference on Electricity Distribution*, (0784):21–24, 2007.

[18] Yuandi Lin, Lijun Yang, Ruijin Liao, Weidong Sun, and Yiyi Zhang. Effect of oil replacement on furfural analysis and aging assessment of power transformers. *IEEE Transactions on Dielectrics and Electrical Insulation*, 22(5):2611–2619, 2015.

[19] Ashkan Teymouri and Behrooz Vahidi. CO2/CO concentration ratio: A complementary method for determining the degree of polymerization of power transformer paper insulation. *IEEE Electrical Insulation Magazine*, 33(1):24–30, 2017.

[20] B. García, D. Urquiza, and J. C. Burgos. Investigating the influence of moisture on the 2FAL generation rate of transformers: A new model to estimate the DP of cellulosic insulation. *Electric Power Systems Research*, 140:87–94, 2016.

[21] Ahmed E.B. Abu-Elanien, M. M.A. Salama, and M. Ibrahim. Calculation of a health index for oil-immersed transformers rated under 69 kV using fuzzy logic. *IEEE Transactions on Power Delivery*, 27(4):2029–2036, 2012.

[22] S Hmood and S Islam. A New Fuzzy Logic Approach for Consistent Interpretation of Dissolved Gas-in-Oil Analysis. *IEEE Transactions on Dielectrics and Electrical Insulation*, 20(6):2343–2349, 2013.

[23] Hasmat Malik, Amit Kumar Yadav, Sukumar Mishra, and Tarkeshwar Mehto. Application of neuro-fuzzy scheme to investigate the winding insulation paper deterioration in oil-immersed power transformer. *International Journal of Electrical Power and Energy Systems*, 53(1):256–271, 2013.

[24] Amy J.C. Trappey, Charles V. Trappey, Lin Ma, and Jimmy C.M. Chang. Intelligent engineering asset management system for power transformer maintenance decision supports under various operating conditions. *Computers and Industrial Engineering*, 84:3–11, 2015.

[25] Dan Zhou, Chengrong Li, and Zhongdong Wang. Power transformer lifetime modeling. *In Proceedings of IEEE 2012 Prognostics and System Health Management Conference, PHM-2012*, pages 8–14, 2012.

[26] Iar Gray. A guide to transformer oil analysis. *Transformer Chemistry Services*, pages 1–12, 2009.

[27] Xiang Zhang and Ernst Gockenbach. Asset-management of transformers based on condition monitoring and standard diagnosis. *IEEE Electrical Insulation Magazine*, 24(4):26–40, 2008.

[28] Di He, Yu Zhang, Chuangxin Guo, Senior Member, and Jinjiang Zhang. Failure Probability Model of Transmission and Transformation Equipment for Risk Assessment. *In 2016 IEEE Power and Energy Society General Meeting (PESGM)*, (1):1–5, 2016.

[29] Richard Wakelen. DNO common network asset indices methodology. 2015.